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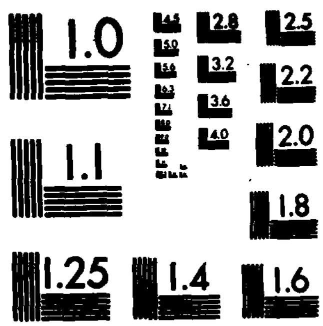

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ABSTRACT

An experiment was conducted to determine the feasibility of using a commercially available thermoelectric device as a heat flux gage at near ambient conditions. In certain research applications, the thermoelectric heat flux gage can provide a relatively simple means to model a warm fluid--cold wall convection environment. The experiment showed that heat flux through the gage could be correlated within 2.5 percent with a simple algebraic equation which considered the thermoelectric current through the device and the hot and cold side temperatures.

NOMENCLATURE

α	Seebeck parameter, V/K
C	Heat capacity of water, W-sec/kg-K
I_{TED}	TED Current, A
k	Heat conduction parameter, W/K
$\dot{m}_w$	mass flow rate of cooling water, kg/sec
q_c	Heat flux at cold plate, W
q_k	Heat conducted, W
q_{1c}	Heat gain at cold plate, W
q_p	Peltier heat, W
q_R	Resistence heat, W
R	Resistence parameter, ohms
T_{amb}	Ambient temperature, K
T_c	Cold plate temperature, K
T_g	Guard plate temperature, K
T_H	Hot plate temperature, K
ΔT_w	Water temperature rise, K

INTRODUCTION

A common method of making convective heat flux measurements between a surface and a flowing gas at near ambient conditions is to use an electric heater attached to the surface. A properly guarded electric heater can supply a simply measured amount of heat. Using this method a temperature gradient is set up in the fluid with the wall warmer than the fluid thus heat flow is from the wall to the fluid. This has been done at various laboratories to measure the heat flux distribution around a simulated turbine blade; see for example Refs. 1 and 2. Participants in a workshop held at the NASA Lewis Research Center on heat transfer research in gas turbine engines (3) questioned the confidence researchers have in heat transfer measurements made with the heat flux from blade to gas when in the actual turbine the direction of flux is from gas to blade.

The reason for such concern is that a heated laminar boundary layer will transition to turbulent flow at a lower Reynolds number than a cooled laminar boundary layer. This has been shown experimentally by Linke and analytically by Tollmien (4). For research applications where the heat flux is into the wall and where the condition of the boundary layer is important (as in turbine blade heat transfer) the electric heater heat flux gage may not be the appropriate instrument. A gage which causes heat to flow from the fluid to the wall in a controllable manner would prove useful.

There are methods available for measuring heat flux when the direction of flux is from fluid to wall. In Ref. 5, for example, a cold fluid was circulated in passages beneath the surface while a heated gas flowed over the surface. Gardon type gages then measured the local surface heat flux. This method was cumbersome, involving pumps and heat exchangers for liquid flow, heating of the gas, and a large amount of sensitive instrumentation producing microvolt signals.

A simpler approach to obtain a cooled wall would be to employ thermoelectric devices which are small commercially available solid state heat pumps. The thermoelectrtic device (TED) is an array of paired semiconductor junctions which, when energized, move heat from one junction to the other. Because the rate of heat pumping is proportional to the current used, it was thought these devices could be used as a heat flux gage in moderate temperature research applications where the direction of the heat flux must be toward the surface.

A limited amount of work has been published concerning thermoelectrtic devices. Manufacturers product catalogs and application notes give general information on the use of their products (6-8). References 9 to 11 provide theoretical background for thermoelectric materials and processes. Most of the sources available, however, are concerned with TED use in refrigeration applications where the amount of heat to be pumped is approximately constant, and so, only of concern during initial design of the appliance. These data are of marginal use in predicting the characteristics of a thermoelectric heat flux gage where the heat flux and temperature are not fixed. To make this device useful as a heat flux gage, a simple way to correlate heat flux to the TED operating parameters was needed.

A preliminary study was conducted to determine if a thermoelectric device could be used practically as a heat flux gage. A prototype thermoelectric heat flux gage was built. The gage consisted of a readily available TED sandwiched between two copper plates one of which had provisions for water cooling. An electric heater was used as a source of heat to be removed by the prototype gage.

Results of preliminary tests reported in Ref. 12 showed that the heat flux data could be correlated to the electric current through the thermoelectric device and the hot and cold plate temperatures by a simple algebraic equation. The data from this preliminary test was limited to a single hot plate temperature of 303 K, however. This was throught to be a serious limitation. Further tests, which are the subject of this paper, have been conducted at two additional hot plate temperatures, 298 and 313 K and show the generality of the correlation previously derived.

In this paper, the correlating equation will be developed from general thermoelectric theory. The experimental apparatus used for the calibration tests will be described and the test procedure will be outlined. Finally, the results of the test will be presented in terms of the correlating equation.

GENERAL THERMOELECTRIC THEORY

The thermoelectric device (TED) is a solid state heat pump. It is an array of paired N and P semiconductor junctions. Figure 1 shows a single semiconductor pair. If a temperature difference is held across the two junctions, an electrical potential appears at the terminals of the device. This is the Seebeck effect (simple thermocouple effect). As shown in Fig. 1, however, when a source of electric current is applied across the TED, one junction becomes cold, the other hot. This is the Peltier effect which is exploited in the thermoelectric heat flux gage.

For use as a heat flux gage it is necessary to be able to determine the amount of heat being removed from the cold side of the device. There are three basic modes of heat transfer in a TED (11).

Peltier Effect. - The Peltier effect is the heat pumping process when the device is energized electrically. The heat that is pumped is moved from the cold to the hot side

$$q_p = \alpha I_{TED} T_C \qquad (1)$$

(q is designated as positive when it flows from cold to hot side)

Heat Conduction. - Because the unit produces a temperature gradient there will be heat conducted through the device. It is important to note that this heat travels from the hot to the cold side and so is taken as negative.

$$q_k = -k(T_H - T_C) \qquad (2)$$

Resistence Heating. - Electric power input to the device creates heat which is assumed dissipated equally on both the hot and cold side. In considering TED's use as a heat flux gage we only need to consider heat dissipated at the cold side. Thus,

$$q_R = \frac{I_{TED}^2 R}{2} \qquad (3)$$

Combining these terms yields an expression for the heat removed from the cold side

$$q_C = \alpha I_{TED} T_C - k(T_H - T_C) - \frac{I_{TED}^2 R}{2} \qquad (4)$$

The purpose of this study was to determine if equation (4) could be used to calibrate a TED for use as a heat flux gage. If the parameters α, R, and k are constant over a useful range of both hot and cold plate temperatures, then the TED should prove a practical research tool.

APPARATUS

Thermoelectric devices are commercially available in a wide range of sizes and capacities. Sizes are available from just a few square millimeters to several square centimeters. Thickness of these devices is usually from 0.4 to 0.5 cm. The maximum rate of heat pumping is from about one quarter watt to more than 35 W. The upper temperature limit, which is due to the semiconductor material properties, is normally 373 to 423 K.

One of the many TED's available on the market was chosen as representative for this preliminary investigation. This device was 3.96 cm (1.56 in.) square and 0.381 cm (0.15 in.) thick. There was 127 semiconductor pairs. The semiconductor was a quarternary alloy of bismuth, tellurium, selenium, and antimony.

For use as a heat flux gage, in this experiment 0.635 cm (1/4 in.) thick copper plates were attached to each side of the TED. Both plates were fitted with four chromel-alumel thermocouples soft soldered in grooves on the face that adjoins the TED. The thermocouples were fabricated following the recommendations in Ref. 13. Figure 2 is a sketch of the test apparatus. Since heat flow was from the cold side to the hot side a 0.476 cm (3/16 in.) O.D. copper tube was soldered to the hot side plate. Water was circulated through this tube to remove heat. Two Cr-Al thermocouples, connected in parallel, recorded inlet and exit water temperature difference. Cr-Al thermocouples also measured ambient temperature on the outside of the insulation surrounding the test TED gage. The copper plates were attached to the TED using the manufacturer's recommendation. The hot side of the TED was soldered to the copper plate using a low temperature indium-tin solder. The cold side was in mechanical contact with the copper plate and a thin layer of silicon heat sink compound was used to insure low thermal contact resistence.

The calibration procedure required that an easily measured amount of heat be supplied to the cold plate of the gage. This was accomplished with a metal foil electric heater. This heater was attached directly to the exposed surface of the cold side copper plate using a pressure sensitive adhesive. The copper plate and electric heater designated "guard copper plate" were used in the tests of Ref. 12 but not used in this series of tests. The whole assembly was surrounded with insulation to minimize heat loss to the surroundings.

PROCEDURE AND DATA REDUCTION

Heat Loss Calibration. - During the calibration and operation of the TED heat flux gage, the cold plate was normally below ambient temperature. Since the insulation used was not perfect, heat must leak from the surroundings to the cold plate. A series of tests was conducted to measure this heat gained by or leaked to the cold plate. These tests were run by energizing the TED but not the electric heater on the cold plate (fig. 2). The temperature rise in the hot plate cooling water and its flow rate were then used to estimate the heat removed from the hot side. The heat leaked to the cold side q_{lc}, was then calculated by subtracting the electric power dissipated in the TED from the heat removed by the water.

$$q_{lc} = \dot{m}_w C \, \Delta T_w - V_{TED} I_{TED} \qquad (5)$$

Figure 3 shows the results of the heat loss calibration. The estimate of heat leaked to the cold plate was near zero except for the three points with the largest difference between ambient and cold plate temperatures. For this reason the heat leaked to the cold plate was ignored when processing the heat flux gage data.

Thermoelectric Heat Flux Gage Calibration. - Tap water, with its temperature limited to a single value around 285 K, was used to remove heat from the hot side. This made running the hot plate over a wide range of temperatues difficult. Three hot plate temperatures, T_H, were run for the gage calibration tests; they were 298, 303, and 313 K. A series of five cold plate temperatures, T_C, were selected somewhat arbitrarily to establish a parametric set. The values selected were 278, 283, 288, 293, and 298 K. The cold plate heater was arbitrarily set while I_{TED} and water flow rate were adjusted to maintain T_H at one of the three chosen temperatures and the desired cold plate temperatue, T_C. At equilibrium all data were recorded and a new point was set by changing the heater power and readjusting I_{TED} and the water flow rate to maintain T_H and T_C. The heat pumped by the device was assumed equal to the electric heater input since the heat leaked was shown to be near zero. The cooling water flow rate and temperature rise were used to check the overall energy balance of the system at each point. The electric heater input plus the heat dissipated in the TED should equal the heat removed by the water. This was found to be true to within about 10 percent for all data points.

RESULTS

A commercially available thermoelectric device was modified for use as a heat flux gage that could provide a simple means to model a warm fluid-cold wall convection environment. An experiment was conducted to determine if the heat flux could be correlated to the thermoelectric device operating parameters. The data gathered during the experiment were fit to Eq. (4) by the method of least squares. It was expected that for the range of temperatures and heat flows used the parameters α, R, and k would be constant. Good correlation of the data and the least squares curve fit of Eq. (4) supports this expectation. Values found were:

$$\alpha = 0.047 \text{ V/K}$$
$$R = 2.26 \text{ ohms}$$
$$k = 0.506 \text{ W/K}$$

These values differ slightly from those presented in Ref. 12 because of the added data for the two additional hot plate temperatures.

Using these constants in Eq. (4) the heat removed from the cold plate can quickly be found by measuring T_H, T_C, and I_{TED}. The reader is cautioned that the constants determined herein may not be generally applicable. Each new device should be calibrated for each particular research application.

The experimental data and Eq. (4) are plotted together in Fig. 4. Several data points were repeated and show excellent agreement. Figure 5 shows a comparison of measured heat flow with that calculated from Eq. (4) for all the data taken. If the prediction of Eq. (4) were perfect, all data points would lie on the line. Average error between data and calculation using the above constants is slightly less than 2.5 percent. The maximum deviation was for the 278 K cold plate temperature; this could be due to heat leaking into the cold plate that was not accounted for in the analysis (i.e., the three non-zero points on Fig. 3).

During the tests the operating parameters of the TED were found to be stable for periods of 2 to 3 hours as long as water temperature, flow rate, and current were kept constant. There is no reason to suspect the device will not be stable indefinitely.

CONCLUSIONS AND RECOMMENDATIONS

A prototype thermoelectric heat flux gage has been built and calibrated. The heat flux gage uses an inexpensive, off-the-shelf, thermoelectric device which requires little modification. In heat transfer research applications where it is important to model a warm fluid-cold wall the thermoelectric heat flux gage could be a useful instrument.

Results of the investigation can be summarized as follows:

1. Agreement of the data and the least squares curve fit to within 2.5 percent shows the form of the correlating equation (Eq. (4)) is correct for this application. One set of constants covers a fairly wide range of hot and cold plate temperatures and heat flows.
2. Data taken shows good repeatability.
3. The operating parameters of the thermoelectric heat flux gage were found to be stable for periods of at least 2 to 3 hours and would probably be so indefinitely.

A point which was not addressed in this study is the effect of TED size on its use as a heat flux gage. For ease of handling and instrumentation a rather large TED was used for these experiments. It is probable that in some experiments a smaller heat flux gage will be needed. An investigation of the effect of size on thermoelectric heat flux gages should be done.

Another point to consider is the effect of average temperature of the gage on the parameters α, R, and k. The temperature range of the device (due to semiconductor properties) covers a wide range, up to 423 K; therefore, the device could be used at nominal temperatures very much higher or lower than the temperatures used in this experiment.

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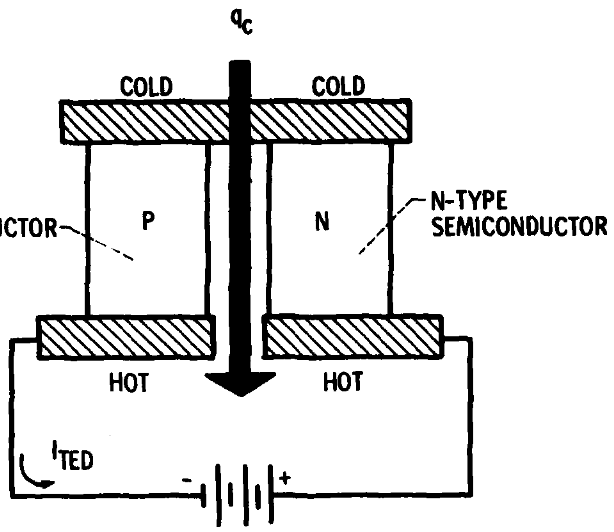


Figure 1. - Typical thermoelectric couple

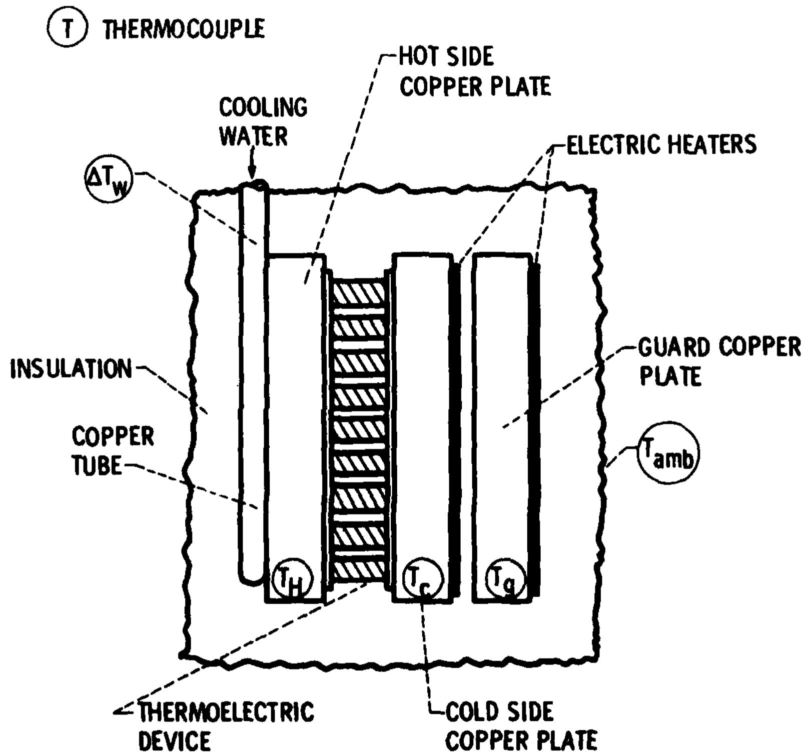


Figure 2. - Thermoelectric heat flux gage calibration rig.

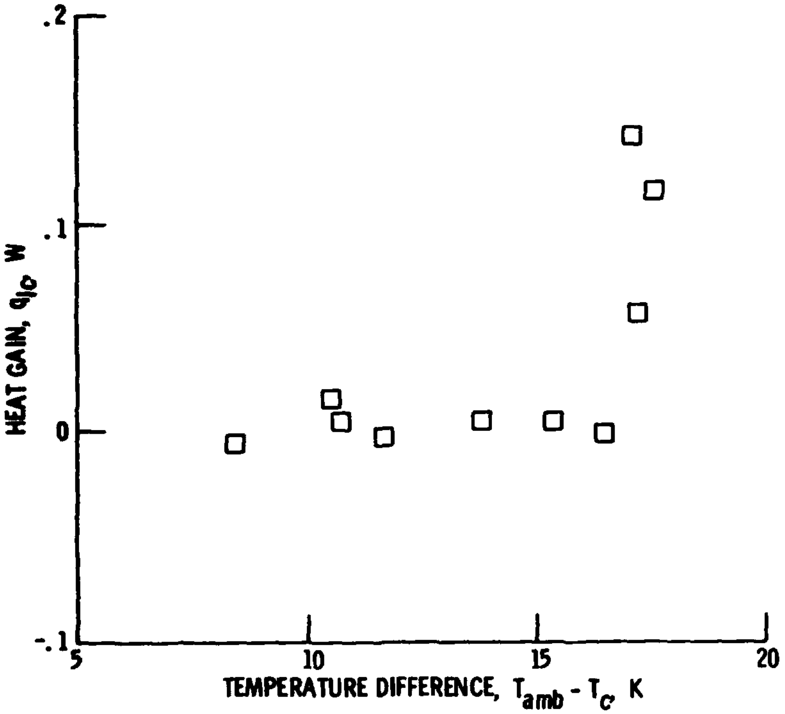
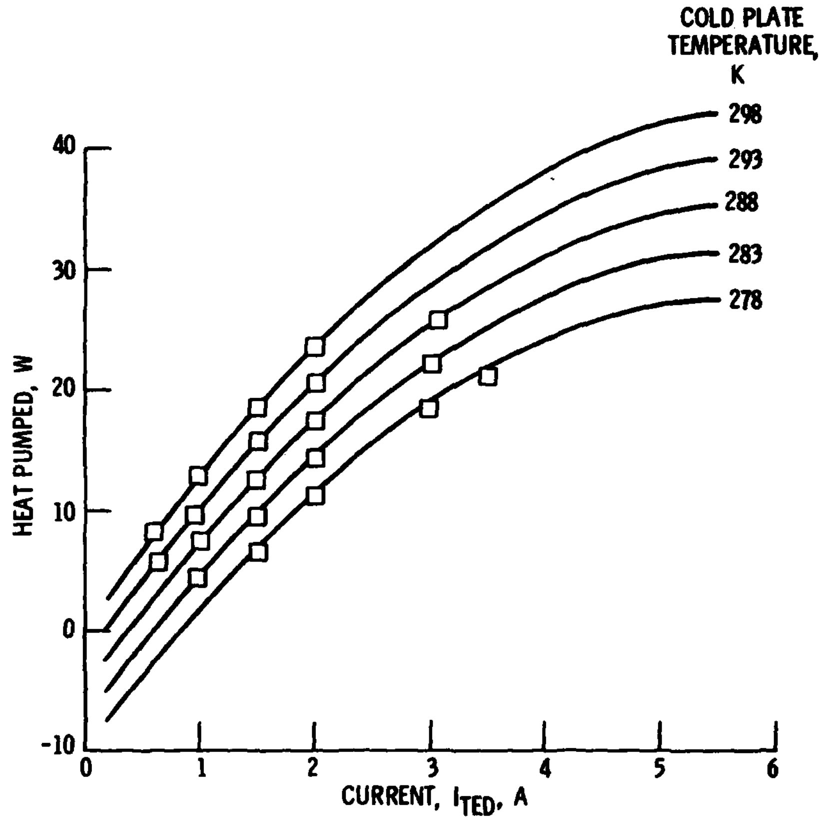
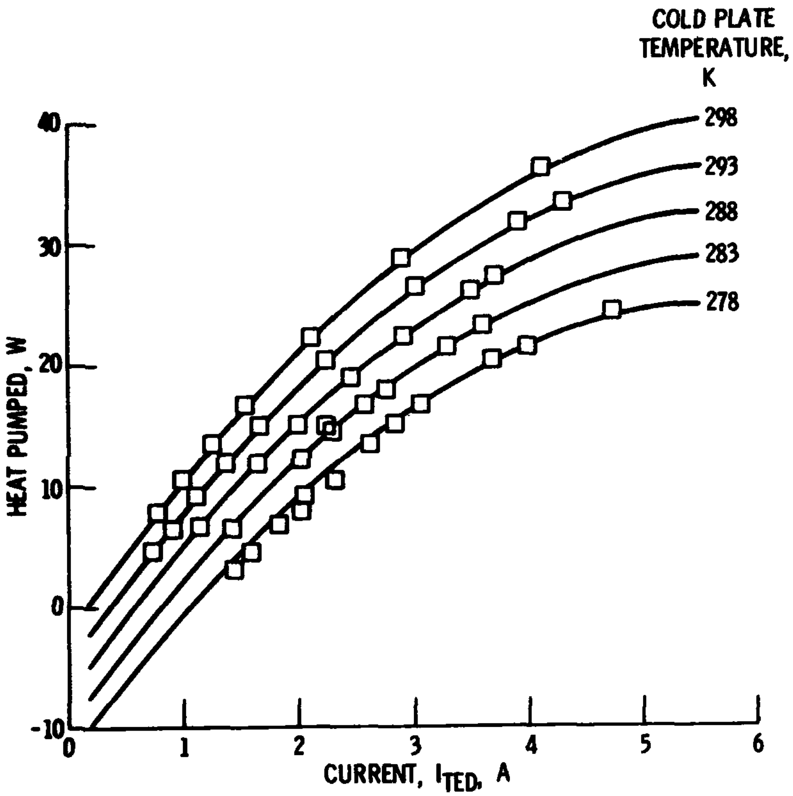


Figure 3. - Heat leaked to cold plate as a function of temperature difference between ambient and cold plate.



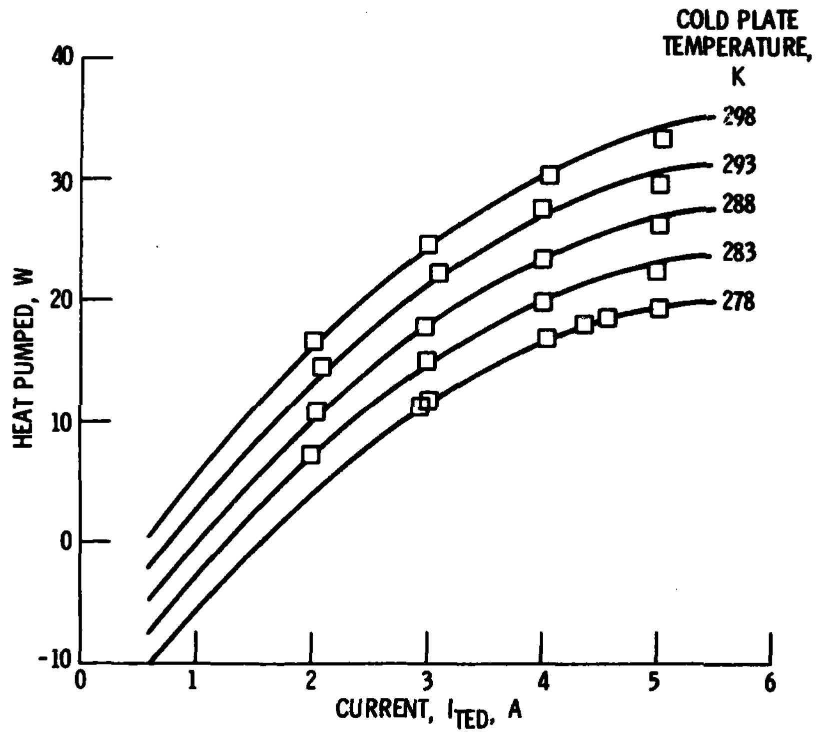
(a) Hot plate temperature 298 K.

Figure 4. - TED heat pumped versus TED current with cold plate temperature a parameter.



(b) Hot plate temperature 303 K.

Figure 4. - Continued.



(c) Hot plate temperature 313 K.

Figure 4. - Concluded.

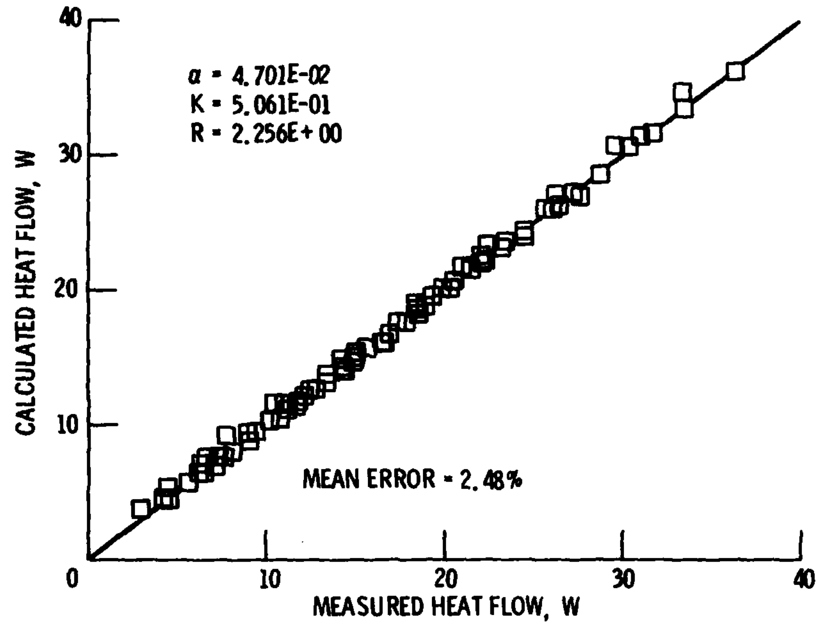


Figure 5. - *Comparison of* heat pumped by the TED heat flux gage to predicted heat flow.

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